

Galaxy Survey On The Fly: Prospects of Rapid Galaxy Cataloging to Aid the Electromagnetic Follow-up of Gravitational-wave Observations

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ABSTRACT

Galaxy catalogs are essential for efficient searches of the electromagnetic counterparts of extragalactic gravitational-wave (GW) signals with highly uncertain localization. We show that one can efficiently catalog galaxies within a short period of time with 1-2 meter-class telescopes such as the Palomar Transient Factory (PTF) or MDM, in response to an observed GW signal from a compact binary coalescence. We find that a rapid galaxy survey is feasible on the relevant time scale of $\lesssim 1$ week, maximum source distance of > 200 Mpc and sky area of 100 deg^2 . With PTF-like telescopes, even 1 day is sufficient for such a survey. This catalog can then be provided to other telescopes to aid electromagnetic follow-up observations to find kilonovae from binary coalescences, as well as other sources. We consider $H\alpha$ observations, which track the star formation rate and are therefore correlated with the rate of compact binary mergers. $H\alpha$ surveys are also able to filter out galaxies that are farther away than the maximum GW source distance. Rapid galaxy surveys that follow GW triggers could achieve $\sim 90\%$ completeness with respect to star formation rate, which is currently unavailable. This will significantly reduce the required effort and enhance the immediate availability of catalogs compared to possible future all-sky surveys.

Subject headings: gravitational waves; methods: observational

1. Introduction

The detection of gravitational waves (GW) from compact binary coalescences is expected to commence in the near future with the completion of the advanced LIGO detectors (Harry & the LIGO Scientific Collaboration 2010) next year and advanced Virgo (The Virgo Collaboration 2009) soon after (LIGO Scientific Collaboration et al. 2013). GWs will enable the examination of binary coalescences, along with other phenomena, from new perspectives (Abbott et al. 2009; Abadie et al. 2010; Bartos et al. 2013).

To increase our confidence in the first detections, as well as to acquire complementary information from astrophysical sources, it will be critical to search for the electromagnetic or neutrino counterparts of GW signals. For the case of

neutron star-neutron star and black hole-neutron star mergers, one of the most promising counterparts are kilonovae (Li & Paczyński 1998; Metzger et al. 2010; Metzger & Berger 2012; Kasen et al. 2013; Tanvir et al. 2013). Kilonovae are produced through radioactive decay of r-process elements, which are created in the neutron-rich material ejected during the merger. They produce quasi-isotropic emission that aids detectability compared to beamed, e.g., gamma-ray, emission. With $\gtrsim 10^{41} \text{ erg s}^{-1}$ peak luminosity in the near infrared and lasting for $\gtrsim 1$ week (Kasen et al. 2013), kilonovae represent a bright and long emission that could be observed upon following up a GW signal candidate with a variety of telescopes.

The expected relatively poor localization of GW signals represents a significant difficulty for

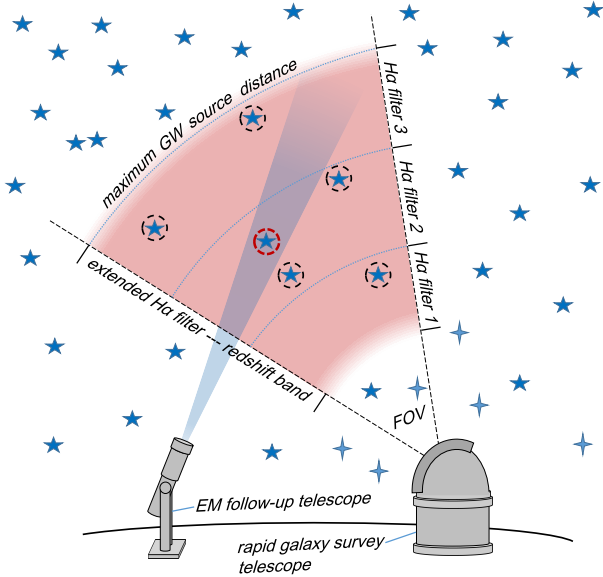


Fig. 1.— Schematic representation of a rapid galaxy survey and electromagnetic follow-up of a GW event. A telescope with large FOV (right) rapidly identifies galaxies within a distance range (red area) defined by the extended $H\alpha$ filter, or alternatively with multiple $H\alpha$ filters covering complementary redshift bands. The upper limit on the covered $H\alpha$ -redshift ensures that bright galaxies beyond the GW sensitivity range do not contaminate the galaxy catalog, while the lower-redshift limit filters out local, e.g., galactic objects. A sensitive, narrow-FOV telescope then searches for the electromagnetic counterpart of the GW event in the directions of the identified galaxies.

follow-up campaigns. Even with a network of 3+ GW detectors, typical events will be localized within $\sim 10 - 100 \text{ deg}^2$. Early on, when only two detectors will be available, or for weak GW signals, the sky area will be $\sim 100 - 1000 \text{ deg}^2$ (LIGO Scientific Collaboration et al. 2013, and references therein). Such a large sky area (i) will result in a large number of false positive events (Kulkarni & Kasliwal 2009), and (ii) will make electromagnetic follow-up difficult with the sufficient depth.

Information on the location of galaxies within the localized sky area and within the sensitivity range of GW observations can significantly improve the potential for detection. Compact binary mergers are expected to occur in or near galaxies (Fong et al. 2010). Searching in the vicinity of galaxies is therefore sufficient to cover all mergers. In the following calculations we adopt a 200 Mpc maximum range for GW detection from neutron star-neutron star mergers, while in Section 5 we then extrapolate the results to greater distances. 200 Mpc is the fiducial direction- and orientation-averaged range for the advanced LIGO-Virgo detectors. Under favorable direction/orientation, neutron-star binary mergers will be detectable out to $\sim 500 \text{ Mpc}$ (e.g., Bartos et al. 2013). Within this range the expected, albeit uncertain, rate of neutron star-neutron star mergers is $0.4 - 400 \text{ yr}^{-1}$, most likely around 40 yr^{-1} (Abadie et al. 2010).

To estimate the reduction of false positives due to using galaxy directions, one can consider the results of Nissanke et al. (2013), who find that the number of galaxies within this volume is $\sim 8 \text{ deg}^{-2}$ within 200 Mpc. For 100 deg^2 sky area, scaling the results of Nissanke et al. (2013) yields a total sky area occupied by the galaxies within 200 Mpc to be $\sim 0.04 \text{ deg}^2$, corresponding to $\mathcal{O}(10^3)$ reduction in the rate of false positives.

Similarly to follow-up surveys carried out for initial LIGO-Virgo (Kanner et al. 2008; Aasi et al. 2014), galaxy locations can also help prioritize among directions followed up by telescopes with limited field of view (FOV). The advantage of prioritization will be most pronounced for these narrow-FOV telescopes. Consider, for example, a telescope with $\sim 15' \times 15'$ FOV (Giant Magellan/IMACS, Long Camera Mode; Bigelow et al. 1998). Such FOV corresponds to an average of ~ 0.5 galaxies within 200 Mpc. Assuming uniform random galaxy distribution, the direction with the

most galaxies within the FOV will have ~ 4 galaxies, while $\sim 60\%$ of the pointings will cover no galaxy. Prioritizing over which directions to follow up first can therefore significantly improve detection efficiency. Even for instruments with larger FOVs, prioritization will be important. For example, the BlackGEM Array ¹ will consist of 60-cm telescopes, each with 2.7 deg^2 FOV. Such FOV corresponds to ~ 20 galaxies on average within 200 Mpc. For uniform galaxy distribution, the direction with the most galaxies within the FOV will have $\sim 50\%$ more galaxies than a random direction, and about three times more galaxies than the direction with the least number of galaxies within the FOV.

Despite these potential advantages, galaxy catalogs are currently far from being complete for the relevant GW distance reach of $r \sim 200$ Mpc (White et al. 2011; Metzger et al. 2013), making the use of available galaxy catalogs less effective. For instance the galaxy catalog used for GW searches with initial GW detectors is estimated to be about 60% complete with respect to B-band luminosity out to 100 Mpc (White et al. 2011).

In this paper we investigate whether a galaxy catalog can be assembled in 1 week, or even 1 day. We consider a hypothetical $\text{H}\alpha$ search with both the Palomar Transient Factory (PTF; Law et al. 2009), and a 2-meter class telescope at the MDM observatory. We first limit the detection range to 200 Mpc, and then generalize the search sensitivity to greater distances. Here, PTF and MDM are taken as examples to demonstrate the capability of existing and relatively easy-to-access instruments. Rapid surveys will likely be performed by a diverse group of telescopes. As this real-time survey will be critical for optimizing science return, the astronomical interest will be broad.

2. $\text{H}\alpha$ survey requirements and completeness

Star formation rate (SFR) is typically used in GW searches as the tracer of the rate of compact binary mergers (Abadie et al. 2012). The merger rate, nevertheless, is expected to be somewhat delayed compared to SFR, and therefore may also be correlated to the total stellar mass in galax-

ies (e.g., Leibler & Berger 2010). In the following, we explore the prospects of an $\text{H}\alpha$ imaging survey, building on the close connection between $\text{H}\alpha$ emission and the ongoing SFR (e.g., Hirashita et al. 2003). We adopt a survey depth of $F_{\text{lim},\text{H}\alpha} = 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ following Metzger et al. (2013), who find that $F_{\text{lim},\text{H}\alpha}$ corresponds to about 90% completeness in SFR. This completeness threshold is chosen as it ensures the coverage of the majority of the sources, while it limits the observational cost, since the undetected 10% $\text{H}\alpha$ luminosity is emitted by the faintest galaxies. Additionally, Metzger *et al.* estimate that $F_{\text{lim},\text{H}\alpha}$ depth also renders a galaxy catalog about 50% complete with respect to total stellar mass. We note here that, given available survey capability, it can be possible to go to even greater depths and and therefore further increase the completeness of the galaxy catalog.

3. Sensitivity for one pointing

We estimate the required duration of one pointing with a telescope to reach $F_{\text{lim},\text{H}\alpha}$ depth. We first consider a 2-meter class telescope, and for this example we adopt the parameters of the parameters of the Hiltner 2.4 m telescope of the MDM Observatory ². With such telescope size, $F_{\text{lim},\text{H}\alpha}$ corresponds to a photon detection rate of $\phi_{\text{H}\alpha} \sim 16$ ph/s. To measure the $\text{H}\alpha$ flux, we consider an extended $\text{H}\alpha$ filter with $[6530 \text{ \AA}, 6890 \text{ \AA}]$ that covers the $\text{H}\alpha$ lines within $[0 \text{ Mpc}, 200 \text{ Mpc}]$. A similar idea of using multiple narrow-band $\text{H}\alpha$ filters for finding nearby galaxies was suggested earlier for PTF (Nissanke et al. 2013).

The background emissions we take into account are galaxy continuum emission and the night sky brightness. We use an R-band filter to estimate and subtract the background. To estimate the night sky brightness, we consider a sky area with 3 arcsec angular radius at 200 Mpc, corresponding to a half-light radius of ~ 3 kpc, which is the typical galactic half-light radius in the R band (Kauffmann et al. 2003). Under favorable circumstances this corresponds to a photon rate of $\phi_{\text{sky}} \sim 1.3 \times 10^3$ ph/s (Benn & Ellison 1998), which can increase by up to a factor of ~ 7 for unfavorable source direction, moonlight, and solar activity. To estimate galaxy brightness in the R

¹<https://www.astro.ru.nl/wiki/research/blackgemarray>

²http://mdm.kpno.noao.edu/index/MDM_Observatory.html

band, we consider a galaxy at 200 Mpc with R-band absolute magnitude $M_R = -18$, corresponding to a photon rate of $\phi_{\text{galaxy}} \sim 1.8 \times 10^3$ ph/s (Bessell et al. 1998). We choose this fainter M_R since fainter galaxies are more likely to be the ones undetected. For comparison, choosing $M_R = -20$ would decrease the observable sky area below by a factor of two, i.e. the covered sky area is weakly dependent on our choice of M_R . We note that fringing effects for this measurement are likely negligible (see, e.g., Cuillandre et al. 2000 for PTF and Smith et al. 2014 for ZTF).

With these photon rates, we can estimate the minimum observation time t_{obs} required to reach $F_{\text{lim}, H\alpha}$ depth with a signal-to-noise ratio SNR:

$$t_{\text{obs}} \approx \text{SNR}^2 \left(\frac{\phi_{\text{sky}} + \phi_{\text{galaxy}}}{\phi_{H\alpha}^2} \right) \left(\frac{\Delta\lambda_{H\alpha+}}{\Delta\lambda_R} \right)^2, \quad (1)$$

where $\Delta\lambda_{H\alpha+} = 360 \text{ \AA}$ and $\Delta\lambda_R = 1491 \text{ \AA}$ are the widths of the extended H α and R-band filters, respectively. Requiring SNR = 5, under favorable night sky conditions we find $t_{\text{obs}} \approx 40$ s, while under “typical” conditions $t_{\text{obs}} \approx 80$ s.

It is worth considering here the possibility that a kilonova is present in the pointing area that could in principle “wash out” the galaxy as it increases the R-band background with little increase in H α . To examine this scenario, we note that the R-band absolute magnitude $M_R = -18$ considered for the faintest galaxies above corresponds to $\sim 6 \times 10^{41} \text{ erg s}^{-1}$ luminosity. This luminosity is greater than any of the kilonova peak luminosities considered in the literature (Barnes & Kasen 2013; Tanvir et al. 2013; Kasen et al. 2014). For comparison, peak R-band emission described recently by Kasen et al. (2014) is within $2 \times 10^{40} - 4 \times 10^{41} \text{ erg s}^{-1}$, or R-band absolute magnitude of $[-17.6, -14.3]$. This means that even at peak luminosity, kilonova emission will be significantly below the galaxy luminosity. An active kilonovae will therefore not affect the galaxy survey.

We now calculate the sensitivity using the parameters of PTF. We assume that the same filters are used in this case as well. With its 48-inch Samuel Oschin Telescope, the photon detection rate of PTF for $F_{\text{lim}, H\alpha}$ flux is $\phi_{H\alpha} \sim 4$ ph/s. Using the same background photon rate as above, we arrive at $t_{\text{obs}} \approx 140$ s under favorable conditions,

and $t_{\text{obs}} \approx 300$ s under typical conditions.

4. Covered sky area for kilonovae

To estimate the sky area that can be surveyed using MDM to find galaxies for kilonova searches, we consider $t_{\text{obs}} = 80$ s for typical conditions from above, applied for both the H α and R-band observations. We further assume a 30-second CCD readout time, and 5-second slewing time between different directions. We consider a week-long as well as a day-long observation window after which kilonovae can still be detectable, with 6 hours of observation per night. With the $24' \times 24'$ FOV of MDM with its 8K CCD, we find the total surveyed sky area in 1 week to be $\sim 100 \text{ deg}^2$ (or $\sim 15 \text{ deg}^2$ per day). We see that 1 week is sufficient to find galaxies in the relevant sky area for GW observation, while even less time may be sufficient for better localized events, or if multiple MDM-like telescopes are available.

For PTF, we consider $t_{\text{obs}} \approx 300$ s for both H α and R-band observations. We assume a readout time of 31 s (Law et al. 2009), and 5-second slewing. We take the Samuel Oschin Telescope’s FOV on PTF being 8.1 deg^2 , we arrive at a covered sky area of $\sim 1800 \text{ deg}^2$ over a one week period with 6-hours of observation per night (or $\sim 260 \text{ deg}^2$ with 6 hours of observations). We see that even 1 day is sufficient for a PTF-like instrument to survey the sky area of interest following a GW signal. Additionally, this result indicates that a fraction of the 6-hour observation will be sufficient for a PTF-like telescope to cover the GW sky area, or a more detailed analysis can be performed in which more detailed information is obtained from the galaxies, such as their redshift.

5. Distance dependence

While above we considered a fiducial distance of $r = 200$ Mpc, GWs are detectable under favorable directions and orientations for significantly greater distances. At design sensitivity, advanced LIGO-Virgo will be able to detect binary neutron star mergers out to ~ 450 Mpc (Bartos et al. 2013), and black hole-neutron star mergers even farther. It is therefore useful to examine the possibility of extending the distance reach of a rapid galaxy survey.

We estimated the sky area that can be cataloged by PTF or MDM as a function of r . The analysis was done similarly to the one presented above for 200 Mpc. We assumed that $F_{\text{lim}, \text{H}\alpha}$ scales with r^{-2} . We scaled the angular size of the background sky area r^{-2} , and modified the width of the $\text{H}\alpha$ filter to account for the redshift corresponding to r . We found that the covered sky area scales as $r^{-1.8}$. For a maximum source distance of 450 Mpc but otherwise using the same parameters as above, this corresponds to a covered sky area of $\sim 400 \text{ deg}^2$ for PTF and $\sim 30 \text{ deg}^2$ for MDM with 1 week of observation (or $\sim 60 \text{ deg}^2$ for PTF and $\sim 3 \text{ deg}^2$ for MDM with 6 hours of observation). We see that even at this larger distance, ~ 1 -day will be sufficient for PTF-like telescopes for a rapid and comprehensive galaxy survey, while MDM will be able to build a catalog out to this larger distance for better localized GW signals.

6. Conclusion

With the sensitivity of present and planned telescopes, it will be difficult to follow-up a GW signal and efficiently scan $\gtrsim 100 \text{ deg}^2$ of the sky for kilonovae. We investigated the capability of a 1 and a 2-meter-class telescope, PTF and MDM, to find galaxies over a large sky area of $\sim 100 \text{ deg}^2$ within a limited time of $\lesssim 1$ week out to $r \geq 200$ Mpc. Such a rapidly assembled galaxy catalog could be used to guide electromagnetic follow-up searches of GW signals from compact binary mergers by significantly reducing the sky area that needs to be scanned. The 1-week time frame is aimed at aiding the observation of kilonovae, one of the most promising electromagnetic counterparts of compact binary mergers, expected to be bright for over a week. We adopted an $\text{H}\alpha$ survey that can be $\gtrsim 90\%$ complete with respect to star formation rate out to the considered distances. We find that such a survey can find galaxies within a sky area of $\sim 1800 \text{ deg}^2$ for PTF and $\sim 100 \text{ deg}^2$ for MDM, within 1 week out to 200 Mpc. We also find that even 1 day of observation is sufficient to cover $\sim 260 \text{ deg}^2$ for PTF out to 200 Mpc, making PTF capable of assembling the required galaxy catalog in a matter of hours. Further, with such a sensitivity, rapid galaxy surveys with significantly greater source distances can be performed. For 450 Mpc, which is the maximum fiducial source distance for advanced LIGO-Virgo for neutron

star-neutron star mergers, we find that PTF and MDM can survey $\sim 400 \text{ deg}^2$ and $\sim 30 \text{ deg}^2$, respectively, in 1 week, and PTF will be able to survey $\sim 60 \text{ deg}^2$ in 1 day. This result shows that even at this largest fiducial distance, a PTF will be capable of assembling a galaxy catalog in ~ 1 day.

Many other telescopes, with suitable filters, would also be able to scan even larger sky areas over the allowed time window. For instance, PTF will soon be succeeded by the Zwicky Transient Facility (ZTF; Bellm 2014, which will have a much larger FOV of 47 deg^2). With the appropriate filters it will be capable of cataloging galaxies within $\sim 100 \text{ deg}^2$ in less than an hour. Other telescopes of interest include the Sloan Digital Sky Survey (SDSS; Gunn et al. 1998), which could be mounted simultaneously with both the extended $\text{H}\alpha$ and R-band filters, allowing for synchronous observation with greater FOV than MDM. Further possibilities include, but are not limited to, CTIO 4m/DECam ³, Subaru/Suprime-Cam ⁴, SkyMapper ⁵, or, in the longer term, LSST (LSST Science Collaboration et al. 2009).

While the presented analysis demonstrates the feasibility of the rapid assembly of a galaxy catalog, there are several improvements that can be addressed in the future. For instance, the analysis above does not find out the distances of galaxies, beyond establishing that they are within 200 Mpc. This can be remedied by, for instance, multiple, narrower $\text{H}\alpha$ filters that can be used to find galaxy distances. Further, the reconstructed distance of the GW source can also be used to tune the search. It will also be interesting to consider whether the rapid galaxy survey itself can be sensitive to also simultaneously detect the electromagnetic counterparts of GWs. To increase the completeness of the surveyed galaxy catalog with respect to stellar mass (Metzger et al. 2013), one can further consider pursuing a similar rapid survey with wide FOV radio telescopes, such as ASKAP (Johnston et al. 2008). Nevertheless, one may not need very high completeness for effective follow-up observations Hanna et al. (2014). Further, the number

³<http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam>

⁴<http://www.naoj.org/Introduction/instrument/SCam.html>

⁵<http://rsaa.anu.edu.au/observatories/telescopes/skymapper-telescope>

of galactic foreground sources may be reduced by requiring a minimum redshift in designing the extended $H\alpha$ filter. Finally, rapid galaxy cataloging can be done with different techniques, and can involve multiple telescopes, further increasing the covered sky area or the completeness. This technique can aid GW electromagnetic follow-up observations even before comprehensive all sky surveys become available with suitable depths out to ~ 500 Mpc, and remedy the sensitivity limitation due to incompleteness of catalogs from the very first day of GW observations.

Rapid galaxy surveys will require (i) the initial investment of obtaining the appropriate extended or multiple $H\alpha$ filters, and (ii) a continued investment of several hours of telescope time per GW signal candidate of interest. The scientific return of propelling the first GW detections and the following chain of scientific discoveries will be well worth the effort. Further, an added beauty of real-time cataloging is that significant contribution can be realized by accessible telescopes, opening up the field for a broader range of collaborators worldwide.

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